16.1.3 Blood pressure monitoring

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Key messages

- Direct vascular pressure measurements can be safe, accurate, and reliable.
- Understanding the interaction of 'plumbing' and monitoring equipment is required if accurate pressure measurements are to be made.
- Zeroing the monitoring system is one of the most important steps taken in pressure monitoring.
- Simple plumbing set-ups, with short lengths of tubing and few stopcocks, provide the most optimal dynamic response and recording mechanism.
- Fast-flush testing to validate adequate dynamic response is essential for deriving accurate systolic and diastolic pressures.

Introduction

Invasive blood pressure monitoring incorporates mechanical and electronic technologies that were formerly only used in the heart catheterization laboratory. With the introduction of disposable devices and modern computerized bedside monitors, clinicians can now conveniently obtain accurate and timely arterial and pulmonary artery pressures. To obtain and maintain the most accurate pressure waveforms and measurements, and to minimize risks to patients, clinicians must understand the principles of operation of these monitoring systems. The two principal purposes for inserting an arterial or pulmonary artery catheter are to measure intravascular pressures and to withdraw blood samples for blood gas or other biochemical analysis.

Continuous and accurate assessment of blood pressures can only be made by inserting vascular catheters. Having pressures displayed continuously permits timely detection of dangerous hemodynamic events and permits display of information to initiate or titrate patient therapy. However, invasive pressure monitoring provides accurate information only when correct equipment and techniques are used.

Equipment

The equipment used to measure blood pressures comprises two components (Fig. 1).

1. The plumbing system consists of a fluid-filled catheter, stopcocks, pressure tubing, a continuous-flush device with its pressurized fluid source, and a transducer.

2. The monitoring system consists of the following electronic and display components: the excitation voltage source for the transducer, a zero control, an oscilloscope display, and a processor to derive measures for the digital display (systolic, diastolic, mean pressures, and heart rate).

Plumbing system

The components comprising the plumbing system must always be kept sterile because the fluid contained within them comes into direct contact with the patient's blood. Most of these components are rather inexpensive and thus are single-use devices.

Catheter

Arterial catheters should be as small in diameter as is practical. The smaller the diameter, the less is the risk of obstruction of the artery. However, the wall must be thick enough to prevent kinking and obstruction of the catheter. The length of the catheter insertion should be sufficient to prevent spontaneous ejection from the artery. The diameter and length of the pulmonary artery catheter are set by the number of lumens required and the length of catheter required to reach the pulmonary artery. The diameter of each lumen is small and, coupled with the long length of the catheter, results in a large resistance which makes it difficult to achieve adequate dynamic response.

Stopcocks

A stopcock is usually located near the catheter connection and is as a site for blood withdrawal for blood gas or similar analyses. V filling the plumbing system great care should be taken to ensur all the central cavities of all stopcocks are filled with fluid. Air bu can lead to embolism if they are 'flushed' into the patient and ca diminish the fidelity of the pressure recording. In addition, stop are a vulnerable site for patient contamination. Hands shou washed before stopcocks are touched, open stopcock ports sh never be touched, and ports not in active use should be co Each connection in the plumbing system, particularly those invo stopcocks, can be problematic. The connections present a discontinuity in the fluid pathway and become sites for entrap of air bubbles. Unfilled central cavities of stopcocks are a fre source of air bubbles that distort dynamic response.

Pressure tubing

The catheter and stopcock are normally connected to the pre transducer with pressure tubing. Since the fluid-filled col between the catheter tip and the transducer must faithfully trar the patient's pressure waveform, the tubing should be short (typi less than 50 cm) and non-elastic (soft venous tubing should n used). Long lengths of tubing add resistance to the pressure wave as it is transmitted from the catheter tip to the pressure transd Such resistance distorts the transmission of the pressure wavel With elastic tubing, the pressure signal is distorted, 'pulsating pressure tubing, and therefore the signal detected by the ext pressure transducer is distorted.

Continuous-flush device and pressurized fluid source

The continuous-flush device with its attached pressurized source is used to fill the plumbing system. The device contains a controlled 'leak' so that it infuses from 1 to 3 ml/h of fluid througl plumbing system and helps prevent clot formation at the cathete The fluid source is usually an intravenous bag of normal saline p surized in a cuff to 300 mmHg. The bag of saline should have th expelled before connecting it to the plumbing system to preven embolism as it empties. A microdrip chamber should be attach the fluid-filled source so that the flow rate can occasionall monitored to ensure that the bag is pressurized and to detect wh is empty. Since it is impossible to clean and sterilize continuous-

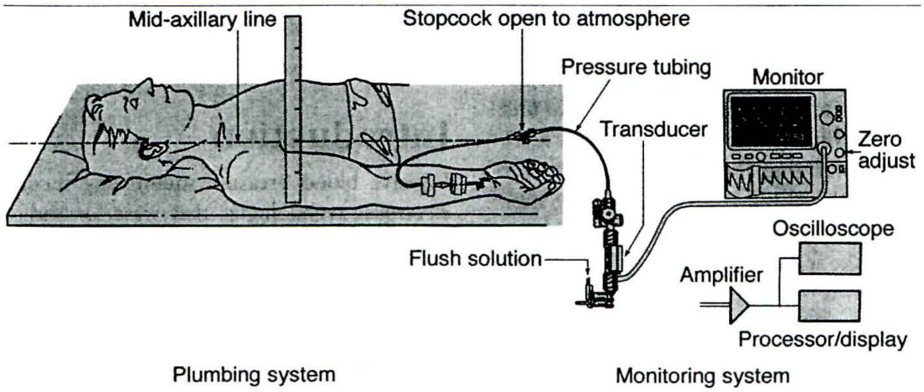

Fig. 1 The plumbing and monitoring systems used for pressure monitoring. The zeroing methodology for a pressure-monitoring system is also shown

ices thoroughly, and to ensure that the tiny 'leak' functions operly for continuous flushing, they should not be reused.

essure transducer

ssure transducers are used to convert the patient's pressure signal to an electrical signal. Modern blood pressure transducers have sulted from a remarkable set of advances in technology. miconductor technology has produced the transistor, processor ips for digital watches, and personal calculators. The same hnology is now used to make pressure transducers. These trans-cers are calibrated to within ± 3 per cent accuracy and maintain eir zero set-point. Modern pressure transducers have a sensitivity 5 μV/mmHg applied per volt of excitation voltage. The transducers re remarkably rugged, accurate over time, temperature stabilized, nd relatively inexpensive. Since it is impossible to clean and sterilize sposable transducers thoroughly, they should not be reused.

Monitoring system

Transducer excitation, amplifier, and filter

The sensing elements of most pressure transducers are four resistive elements connected as a Wheatstone bridge. Resistive bridges require the application of an excitation voltage (typically 3–5 V). Modern monitors provide very accurate (± 0.1 per cent) excitation voltages to the transducers. These monitors also contain amplifiers which take the small voltages supplied by the transducer, typically 30 μV/mmHg, and 'magnify' them by about 1000 times. In amplifiers, 'magnification' is called 'gain'. With modern amplifiers, the gain is very stable and is calibrated with an accuracy to about ± 1 per cent. Because of the accuracy, reliability, and stability of both the transducers and amplifiers, it is no longer necessary to calibrate pressure monitors (Cooper and Paulsen 1994; Gardner 1996). Most pressure amplifiers include a low-pass filter to filter out unwanted high-frequency signals.

Zero control

The zero control on a pressure monitor permits the adjustment of the output signal from the monitor to be zero when the fluid–air interface of a designated 'zeroing stopcock' is placed at the mid-axillary position. Once the zeroing process has been completed it is important that the vertical relationship between the patient and the pressure transducer remains fixed. If there is a vertical movement of the transducer or of the patient relative to the transducer, the system must be 're-zeroed.' However, the vertical position of the zeroing stopcock is unimportant once it is closed.

Operational issues

Zeroing

Zeroing the pressure-monitoring system is probably the most important step in establishing the system. Mistakes in zeroing can result in substantial errors in pressure measurement, particularly when measuring pulmonary artery pressures. The zeroing process involves an interaction between the position of the transducer and the stopcock in the plumbing system with the zero control of the monitoring system. For each 10 cm of misalignment of the zeroing point, there is a pressure offset of $10/1.36 = 7.3$ mmHg. Such a misalignment may cause an error of as much as 100 per cent in measurement of central venous pressure. The vertical position of the transducer relative to the patient's mid-axillary line can change, particularly if it is mounted externally. As a result the monitoring system zero should be verified frequently, and always prior to initiation of treatment changes based on pressure data. Proper zeroing is done by opening the appropriate zeroing stopcock to atmosphere and aligning the resulting fluid–air interface point at the patient's mid-axillary line (Fig. 1).

Dynamic response testing

The fluid-filled plumbing system can modify the pressure signal in what is known as a dynamic response distortion (Gardner 1981; Gardner and Hollingsworth 1986). Most pressure-monitoring systems are underdamped (Gardner 1981). Dynamic distortion is caused by modification of the frequency characteristics of the applied pressure waveform as it passes through the plumbing system. The dynamic response of the plumbing system can be tested using a fast-flush test. This is accomplished by first opening the valve of the continuous-flush device and then quickly closing it. For underdamped systems, the rapid closure produces a square wave from which the natural frequency and damping coefficient of the plumbing system can be determined. The natural frequency is determined by measuring the period of a full cycle of oscillation and taking the reciprocal. For example, if the display rate (either oscilloscope or chart

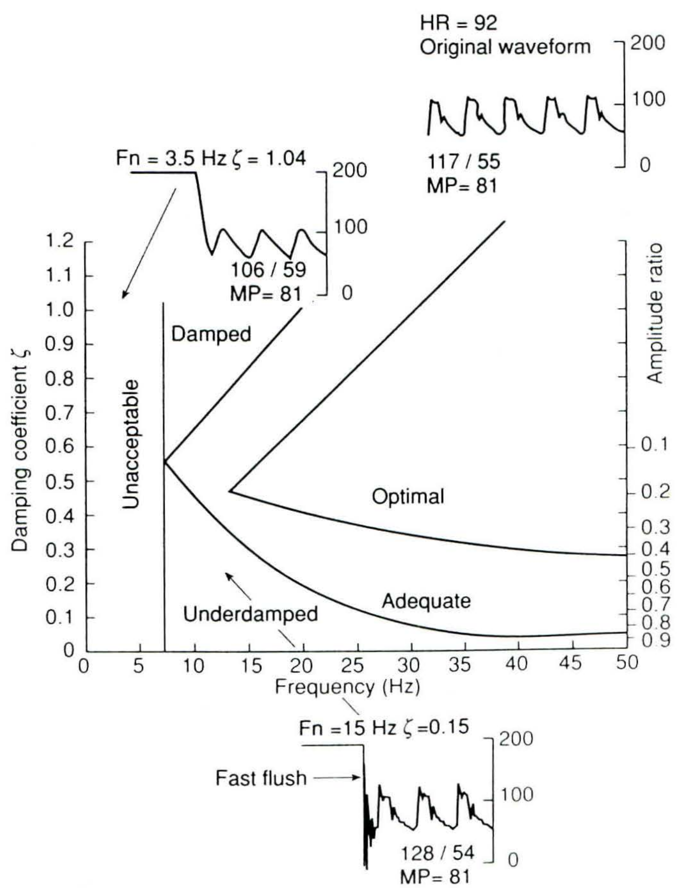

Fig. 2 Dynamic response testing methodology for the pressure-monitoring system. See text for an explanation of how to determine the adequacy of the dynamic response. (Adapted from Gardner (1981).)

Table 1 Relation between arterial pressure waveform and heart condition

Short systolic time	Hypovolemia High peripheral resistance
Marked respiratory swing	Hypovolemia Pericardial effusion Airways obstruction High intrathoracic pressure
Slow systolic upstroke	Poor myocardial contractility High peripheral resistance

recorder) is 25 mm/s and one full cycle of oscillation takes 2 mm, the natural frequency is

$$\frac{25\ \text{mm/s}}{2\ \text{mm/cycle}} = 12.5\ \text{cycles/s} = 12.5\ \text{Hz}.$$

The determination of damping coefficient requires the measurement of the ratio of the amplitude of two succeeding cycles of the resulting oscillating signal following a fast-flush test. The amplitude ratio is then plotted on the non-linear amplitude ratio scale on the far right-hand side of Fig. 2. The damping coefficient ζ is then determined from the linear damping coefficient scale shown in Fig. 2.

Several factors lead to an inadequate dynamic response, including air bubbles in the plumbing system and pressure tubing that is too long or too elastic (Gardner 1981). The best way to enhance the dynamic response of the plumbing system is to maximize the natural frequency. It is clear from Fig. 2 that the higher the natural frequency, the greater the range of damping coefficient can be while still reliably reproducing the pressure waveform. Figure 2 also shows that inadequate dynamic response causes two general types of error. If a system is underdamped, the systolic pressure will tend to be overstated and the diastolic pressure understated. However, if the system is overdamped, the systolic pressure will be understated and diastolic pressure overstated. The pulmonary artery catheter is subjected to 'whip' as it moves in the right ventricle, and this artifact tends to cause major overshoot during the systolic phase of the pressure waveform.

Many clinicians use the shape of the pressure waveform to estimate qualitative information about the heart (Table 1). Since dynamic waveform distortions caused by the plumbing system can mimic many of these conditions, having an adequate dynamic response is essential.

References

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